CHAPTER II

REMOTE SENSING OF CROP MOISTURE STATUS

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ABSTRACT

Remotely sensed thermal imagery may provide a means to assess the extent and severity of water stress on crops over a large area. This would make remote sensing a useful tool for monitoring the effects of drought on crops. Before that becomes a reality, however, crop temperature-moisture stress relationships must be determined. The purposes of this study were to determine some of these relationships and to evaluate some of those factors which will affect the crop temperature data.

Studies were conducted on sorghum in 1974 and on corn in 1978 at two different locations in Nebraska. Plant temperatures were obtained with thermal imagery, with infrared thermometers and with leaf thermocouples. Irrigation treatments in 1978 were designed to permit a plot to receive either full irrigation or to apply a water gradient across the plot during the vegetative pollination and grain fill periods. The gradient treatments resulted in fully-irrigated plants on one side of the plot and dryland plants on the other side.

An examination of the thermal imagery obtained over irrigated and non-irrigated sorghum in 1974 showed that the non-irrigated sorghum plots were at approximately the same temperature as the irrigated plot until mid-afternoon. From then until late evening the non-irrigated sorghum was warmer. There was relative uniformity of temperature across the irrigated sorghum plot but temperatures

were variable across a non-irrigated plot.

The difference in temperature (ΔT) between stressed and non-stressed corn was as great as 12.8 C during mid-afternoon readings. There was a wide range in ΔT from plot to plot, however, reflecting the variability of available soil moisture. Plant height was reduced during the vegetative growth stage by water stress.

Clouds caused more of a decrease in the temperature of stressed plants than of non-stressed plants. The optimum time of day for detecting maximum plant temperature was between 1300 and 1500 solar time. Thus, a good time for making plant temperature measurements in water stress studies would be 1400.

The temperature of well-watered corn as measured with attached leaf thermocouples was within ± 1.2 of the temperature measured with an IR thermometer. The agreement was ± 2.6 C among the stressed plants. Above 27 C, IRT temperatures were slightly cooler than the temperature of the upper sunlit leaves and below 27 C, they were slightly warmer.

Differences in seasonal evapotranspiration (ET) between well-watered and stressed plants were highly correlated with the seasonal accumulation of ΔT.

INTRODUCTION

Reliable estimates of the degree of crop stress occurring at any specified time should be useful to government agencies and others charged with predicting crop yields or assessing the economic impact of reduced yields due to drought. Increasing attention is being given to evaluating the use of remotely sensed crop temperature data for monitoring the extent and severity of drought.

Researchers have demonstrated that when soil water becomes limited, water-stressed plants become warmer than well-watered plants (Tanner, 1963; Palmer, 1965; Bartholic et al., 1972; Ehrler et al., 1978). Although the feasibility of using remotely sensed crop canopy temperature data as an indicator of plant water status has been demonstrated, quantitative data relating canopy temperature to the development of crops over a complete growing season is sparse. Idso et al. (1977) and Jackson et al., (1977) have reported seasonal results for durum wheat (_Triticum durum_ Desf.) grown in Phoenix, Arizona.

The purposes of the study reported here were as follows: 1) to observe the behavior of irrigated and non-irrigated corn (_Zea mays_ L.) and sorghum (_Sorghum bicolor_ L. Moench) with respect to crop temperature; 2) to evaluate the effect of clouds on the temperature of stressed and non-stressed corn and sorghum plants; 3) to determine the optimum time of day to use crop temperature data for detection of maximum plant water stress; 4) to compare the temperature of stressed and non-stressed vegetation as measured with leaf thermocouples with those measured with an infrared thermometer and 5) to describe evapotranspiration (ET) as a function of cumulative seasonal crop temperature data.

MATERIALS AND METHODS

A field of 1.82 ha at the University of Nebraska Agricultural Meteorology Research Laboratory at Mead, Nebraska (41° 09' N; 96° 30' W; 354 m above m.s.l.) was studied with thermal imagery. Sorghum (_Sorghum bicolor_ Moench cv. 'Rs633') was planted on May 16, 1974 in north-south rows on 51 cm centers with 10 plants/m or row.

The field was sprinkler irrigated weekly (about 3.6 cm per application) between June 18 and August 2. The surrounding fields were also planted to sorghum but were not irrigated.

During the growing season, crop temperatures were measured from altitudes of 610 and 1220 m with a thermal scanner* in an aircraft furnished by the Remote Sensing Institute of South Dakota State University. Flight lines were parallel to field rows at the three sites. Flights were made on August 12 and August 26. Tempertures were measured in the 8.7 to 11.5 μm wavelength band at a scanning rate of 80 scans per sec. The temperature resolution of the scanner was 0.4 C and the spatial resolution was 16 cm per 100 m of altitude. Additional information concerning this experiment can be found in Rosenberg et al. (1975).

Most of the data reported here were obtained during the 1978 growing season at the University of Nebraska Sandhills Agricultural Laboratory (SAL) (41° 37' N; 100° 50' W; 975 m above m.s.l.), located about 40 miles north of North Platte, Nebraska.

Canopy temperatures were measured each day throughout the 1978 growing season. Measurements were made with an infrared thermometer (IRT) between 1200 and 1330 solar time on rows 2, 6, 10, 14, 18 and 22 of each plot. Two infrared thermometers were used: a Telatemp model 44 and a Barnes PRT-5. One plot used for IRT measurements was also instrumented with leaf thermocouples at the bottom, middle and top of the canopy on rows 2, 6, 10, 14 and 22. Net radiation was also measured on this plot with a Middleton Model CN6 miniature net radiometer at an elevation of

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*Daedalus Enterprises, Inc., Ann Arbor, Michigan.

3 m above the soil surface.

Soil moisture was measured weekly in each plot with a neutron probe in the same rows as were used for temperature measurements at depths of 15, 30, 60 90 and 150 cm. Rainfall and irrigation were measured with rain gauges installed adjacent to each neutron access tube. The gauges were raised, as the season progressed, to maintain the "catch height" just above the top of the canopy.

Line Source System

Hanks et al. (1976) reported the development of a line source irrigation system. When irrigation sprinklers are spaced closely along a single pipeline, the resulting depth of water application is essentially constant along the line but decreases with distance from it. This results in a "gradient" water application ranging from a maximum at the line to zero at a distance equal to the wetted radius or "throw" of the sprinkler. The actual distance involved depends on the design of the sprinkler system and on wind speed and direction during operation of the system.

Figure 1 shows the growth pattern that might result if such a system were used to irrigate a crop throughout a growing season. The crop near the sprinkler line would receive "full" irrigation while proportionately smaller irrigation amounts would be received by the crop at greater distances from the line. Beyond the reach of the sprinklers, the crop would have available only stored soil water and rainfall to meet its requirements. Single-sprinkler lines or "line sources" have been used by researchers to provide varying quantities of water to experimental plots.

Where crops are planted parallel to the sprinkler line, each

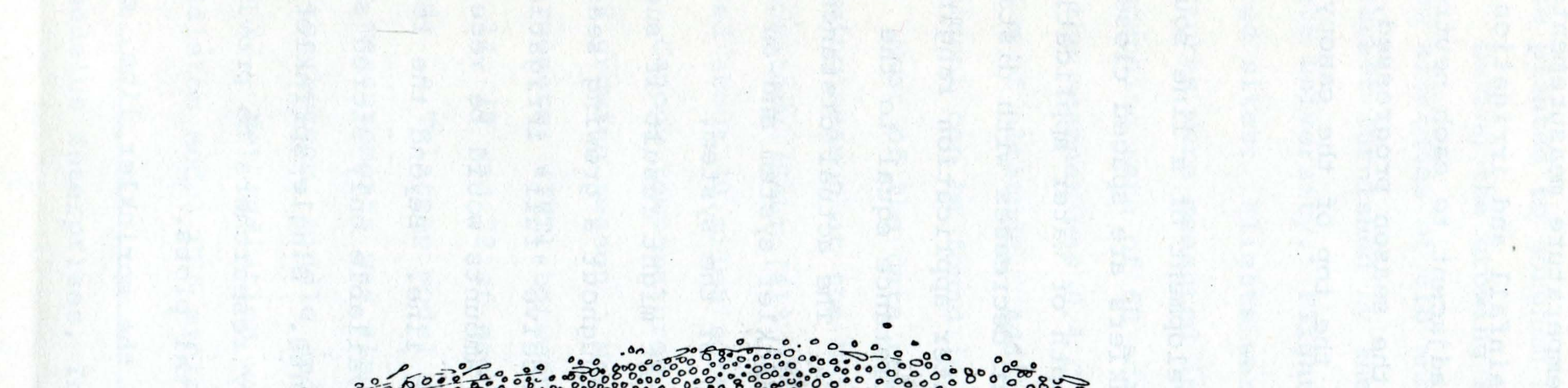

Fig. 1. Sketch showing reduced growth pattern perpendicular to line source system operated on full gradient for the entire growing season.

row becomes, in effect, a different treatment since each row receives a different amount of water than its neighbors to either side. Because of the relatively small differences in applied water betwen neighboring rows, rows can be placed in groups of two, three or four. The group of rows would be considered a single treatment.

Modified Line Source

The irrigation system that we used is a modification of the line source system described above. Two irrigation lines were placed on either side of each plot, as shown in Fig. 2. One line (designated as Full Irrigation) was operated weekly to provide all of the water required by the crop grown in the rows immediately adjacent to it. When the second line (designated as the Treatment Line) was turned off, an irrigation gradient was created across the plot. This is known as a "G" treatment. When both lines are operated, the plot is uniformly irrigated. This is designated as an "I" treatment. Varying levels of stress are created across the plot by imposing a "G" treatment on the plot for designated portions of the growing season. Stress is initiated by switching from an "I" to a "G" treatment and can be terminated by reapplying an "I" treatment.

A sprinkler nozzle and pressure combination was used that provided a nearly linear decrease in the quantity of water that was applied with increasing distance from the sprinkler line. Figure 3 shows the total amount of water applied during the season at various distances from a single-sprinkler line in 1978. There is a nearly linear decrease with distance from the line. During

Fig. 2. Schematic of "full" and "treatment" sprinkler lines and the water application pattern resulting from the operation of individual lines. Total water applicatio is the sum of the amounts from the individual patterns

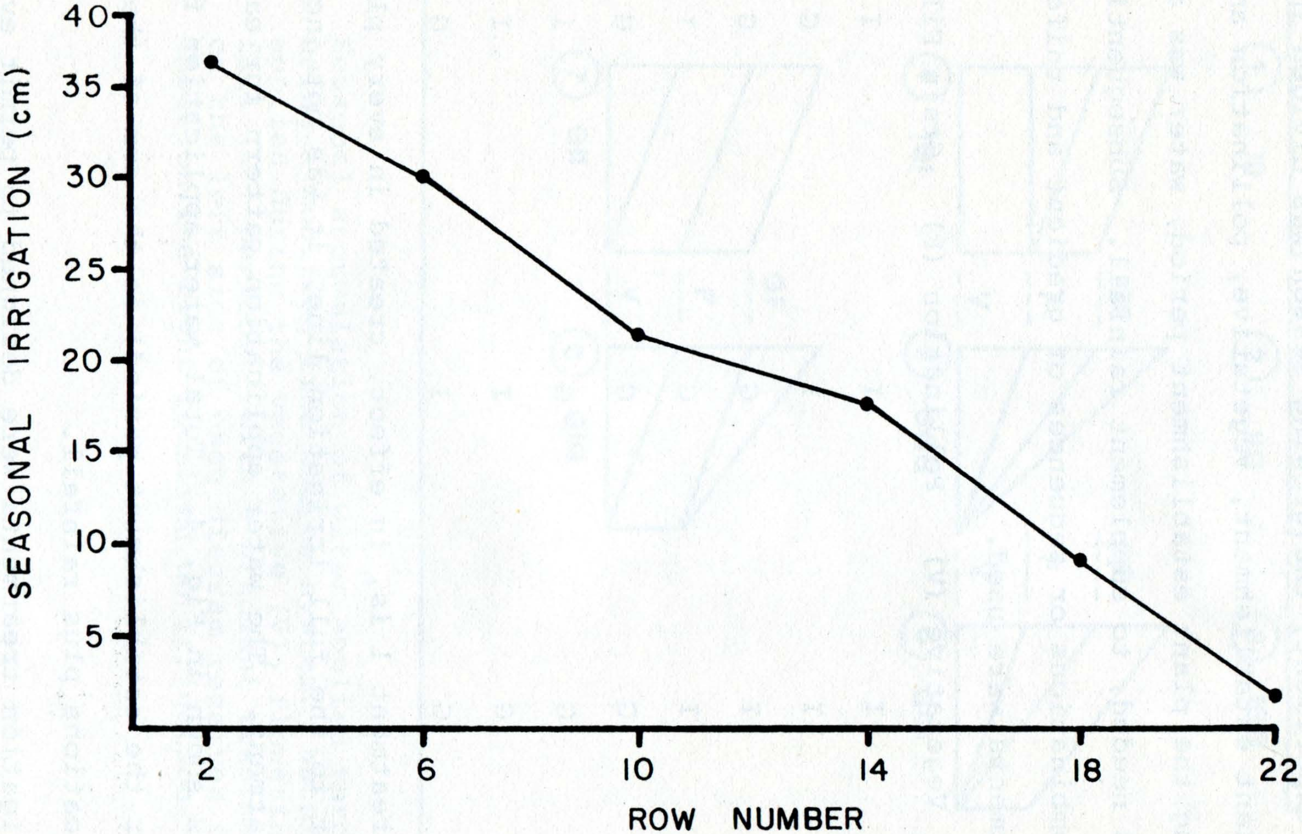

Fig. 3. Accumulated amounts of seasonal irrigation water applied to a G-G-G plot.

any one irrigation, wind effects may cause deviations from the ideal application pattern. However, the sum of two or more irrigations ordinarily compensates for such deviations.

Irrigation Treatments

In our experiment, the growing season was divided into four periods: Plant establishment, vegetative, pollination and grain fill. During the plant establishment period, water was applied uniformly as needed, to supplement rainfall. Subsequently the following combinations or sequences of gradient and uniform irrigation treatments were used.

Treatment	Vegetative (V)	Pollination (F)	Grain Fill (GF)
1.	I	I	I
2.	I	I	G
3.	I	G	G
4.	I	G	I
5.	G	G	G
6.	G	G	I
7.	G	I	I
8.	G	I	G

Since treatment 1 is, in effect, created in every plot in the rows adjacent to the full irrigation line, it was not included as a separate treatment. The water application pattern for each of the treatments is shown in Fig. 4. Total water application for the season (after the establishment period) is the sum of the individual period applications plus rainfall.

The irrigation treatments were designed to permit evaluation of the effects of moisture stress on plant temperature, vegeta-

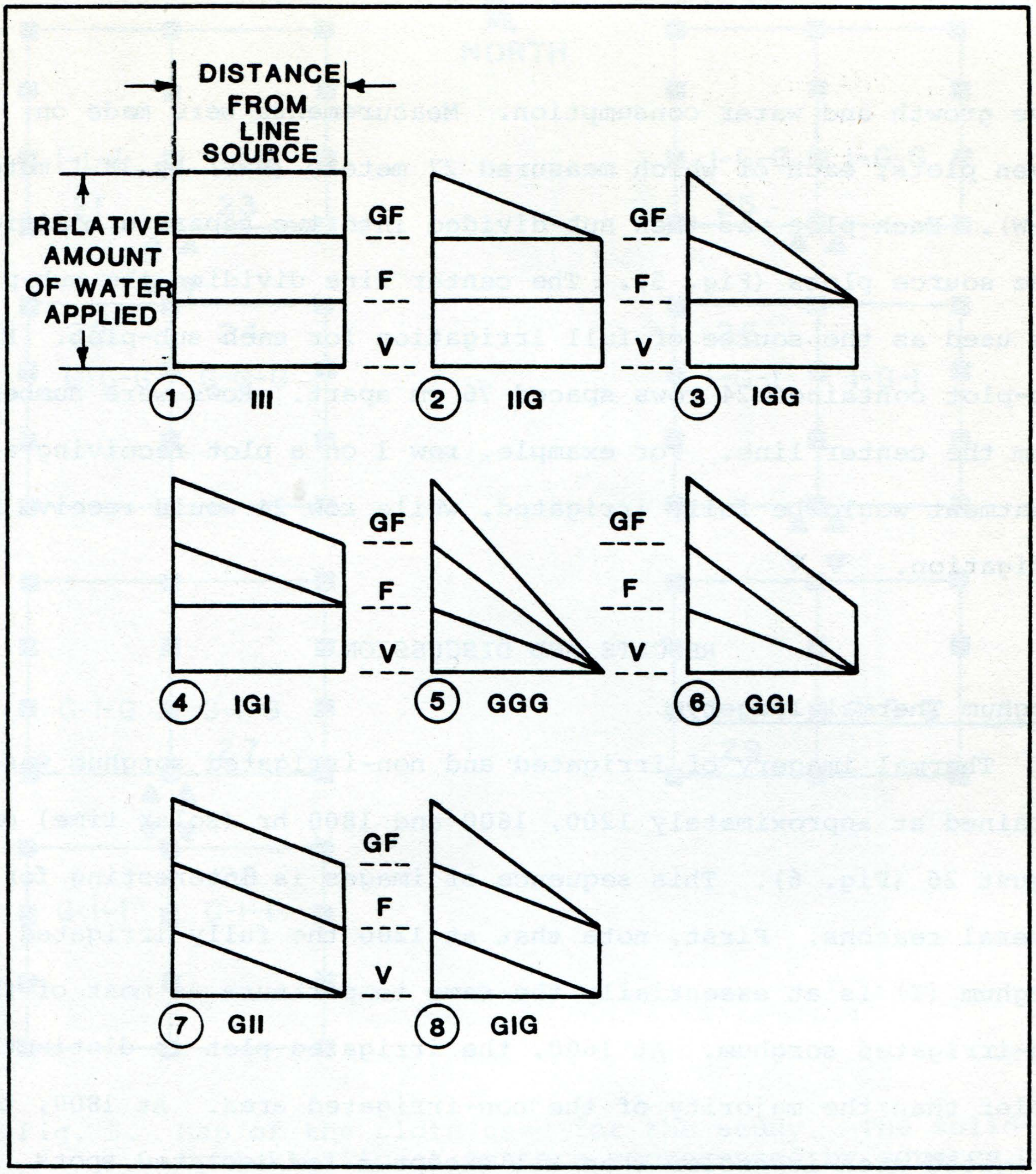

Fig. 4. Seasonal accumulation of water applied through irrigation using a modified line source system. Water treatments were applied during the vegetative (V), flowering (F) and grain-fill (GF) periods. With a gradient treatment (G), plants on the left side of each diagram received full irrigation; those on the right received no irrigation.

tive growth and water consumption. Measurements were made on seven plots, each of which measured 27 meters (N-S) by 19.1 meters (E-W). Each plot was then sub-divided into two separate modified line source plots (Fig. 5). The center line dividing the sub-plots was used as the source of full irrigation for each sub-plot. Each sub-plot contained 24 rows spaced 76 cm apart. Rows were numbered from the center line. For example, row 1 on a plot receiving a G treatment would be fully irrigated, while row 24 would receive no irrigation.

RESULTS AND DISCUSSION

Sorghum Thermal Imagery

Thermal imagery of irrigated and non-irrigated sorghum was obtained at approximately 1200, 1600 and 1800 hr (solar time) on August 26 (Fig. 6). This sequence of images is interesting for several reasons. First, note that at 1200 the fully irrigated sorghum (I) is at essentially the same temperature as most of the non-irrigated sorghum. At 1600, the irrigated plot is distinctly cooler than the majority of the non-irrigated area. At 1800, the irrigated area is cooler than all except a few isolated spots.

Another feature of interest in these images is the temperature pattern of one non-irrigated plot (marked with an N). At 1200, the temperature across this plot were fairly uniform. At 1600 and 1800, however, the temperatures were quite variable on this plot. This indicates that some but not all of the plants in this area had adequate water. Thus, a large temperature variability within a field may signal the presence of soil moisture deficits. Such deficits may occur because of inhomogeneous

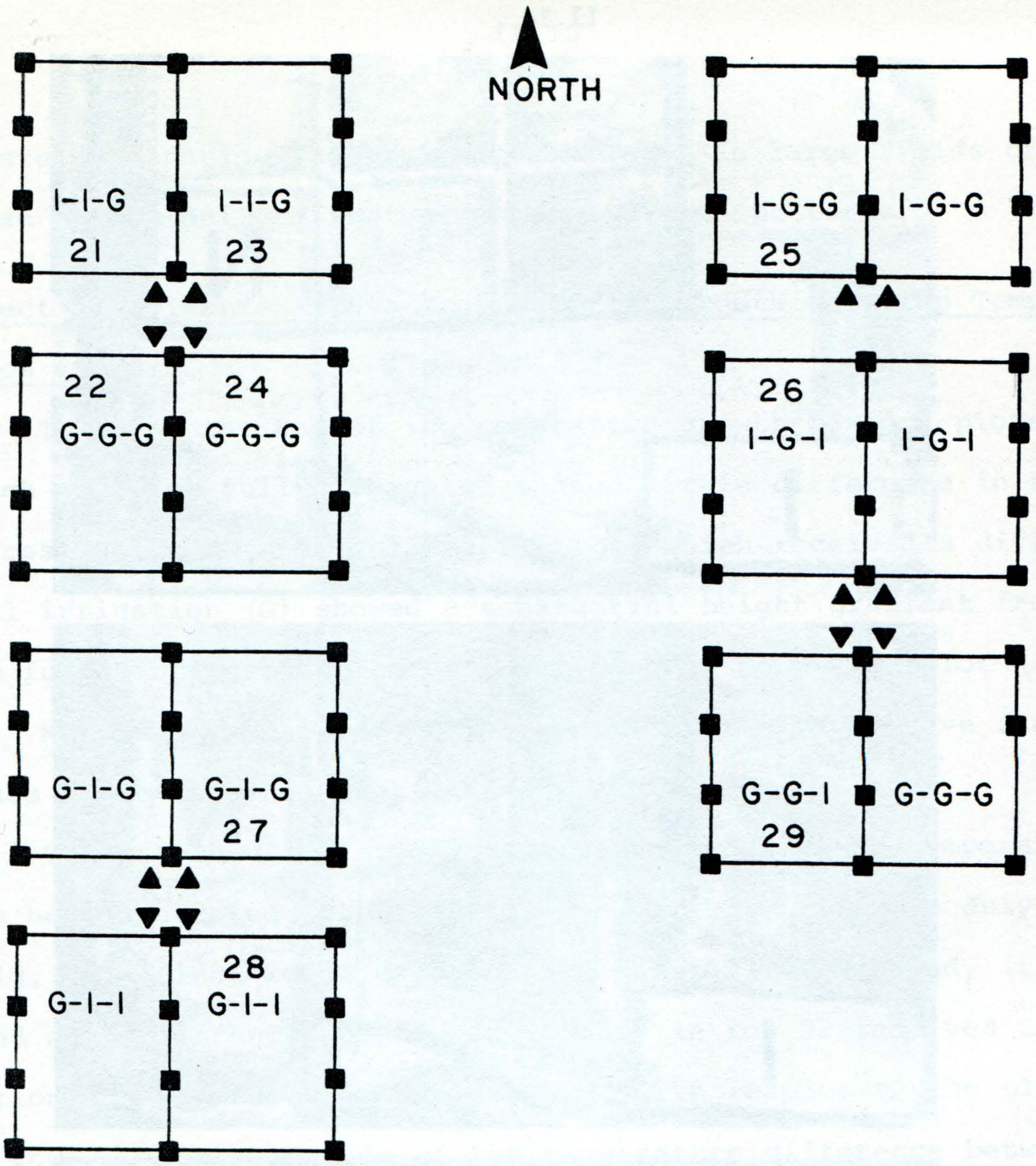

Fig. 5. Map of the plots used for the study. The solid-set sprinkler locations are represented by squares. Row 2 is indicated by the arrows. Plot 22 was instrumented with air and leaf thermocouples. Numbered plots are those on which infrared canopy temperatures were measured.

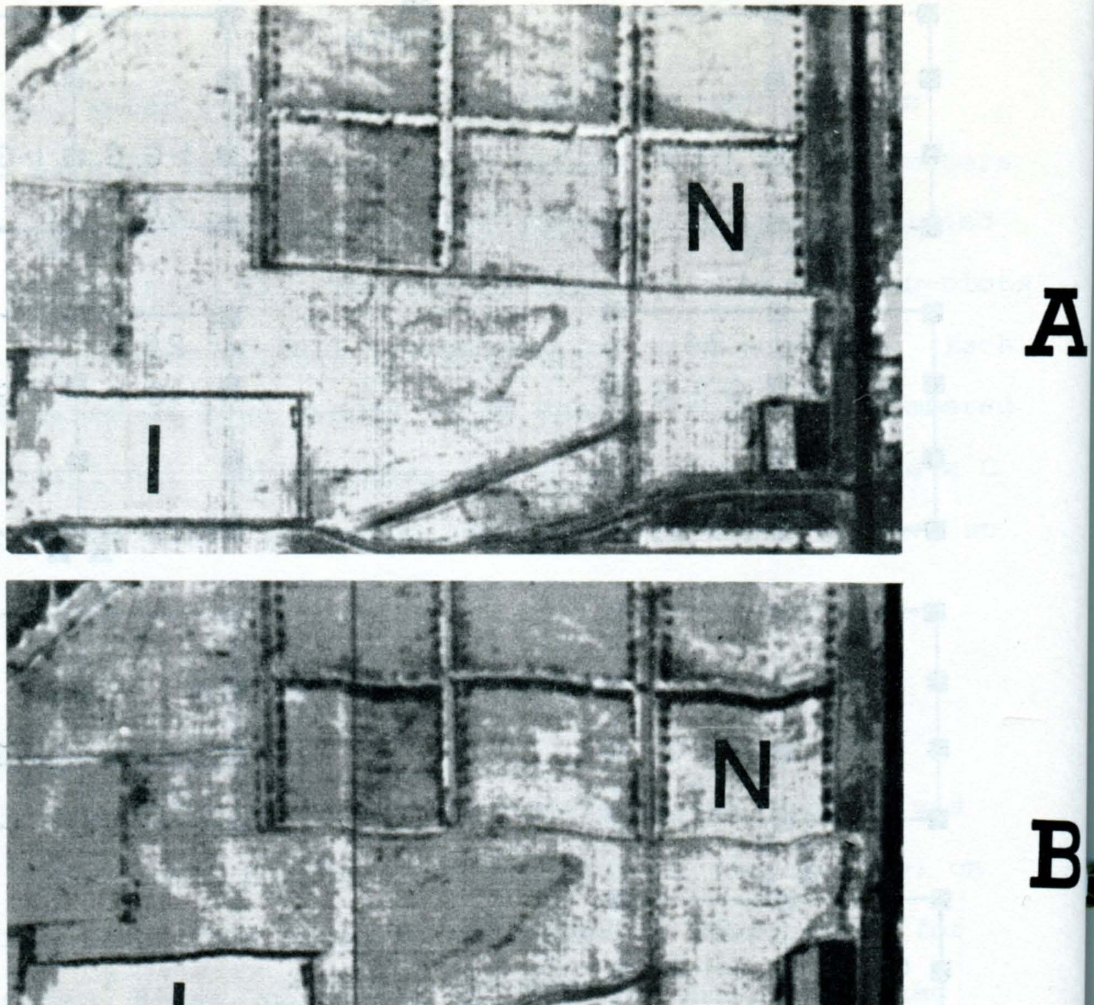

Fig. 6. Thermal imagery of irrigated and non-irrigated sorghum on August 26, 1974, at Mead, Nebraska. An irrigated plot is marked with an I and a non-irrigated plot with an N. The lighter the shade the cooler the temperature. A (1148 h), B (1613 h) and C (1817 h). All remaining areas were planted to non-irrigated sorghum. The lines forming distinctive tic-tac-toe pattern are tree shelter-belts.

moisture retention properties of the soil in large fields or because of non-uniform irrigation application patterns.

Effect of Moisture Stress on Vegetative Growth and Crop Temperatures in Corn

Thus, at the end of the vegetative growth period, plots which had been fully irrigated showed little difference in height across a plot, whereas plants in plots which received a differential irrigation (G) showed a substantial height gradient from the fully irrigated to the non-irrigated side of the plot (Fig. 7). Moisture stress, if prolonged during the vegetative stage, tends to reduce the height of corn plants.

The effect of moisture stress on mid-day plant temperatures can be illustrated with data for the period July 12 to July 18 (Fig. 8). Since row 2 of each plot was fully irrigated, it was used as a reference point. The plants in row 22 received no irrigation and had elevated temperatures with respect to the plants on row 2. The magnitude of the temperature difference between row 22 and row 2 (ΔT_{22}), on a given plot, changed from day to day. This is due to day to day differences in environmental factors which can influence the temperature of a plant.

There is considerable variation in ΔT_{22} between the various plots. That is, some non-irrigated plants had more soil moisture available to them and were cooler than other plants, hence, the variability in the magnitude of stress as suggested by differences in the ΔT_{22} values. The most extreme example of this occurred on July 17, when ΔT_{22} was only 0.8 C in plot 24 but was 12.9 C in plot 27.

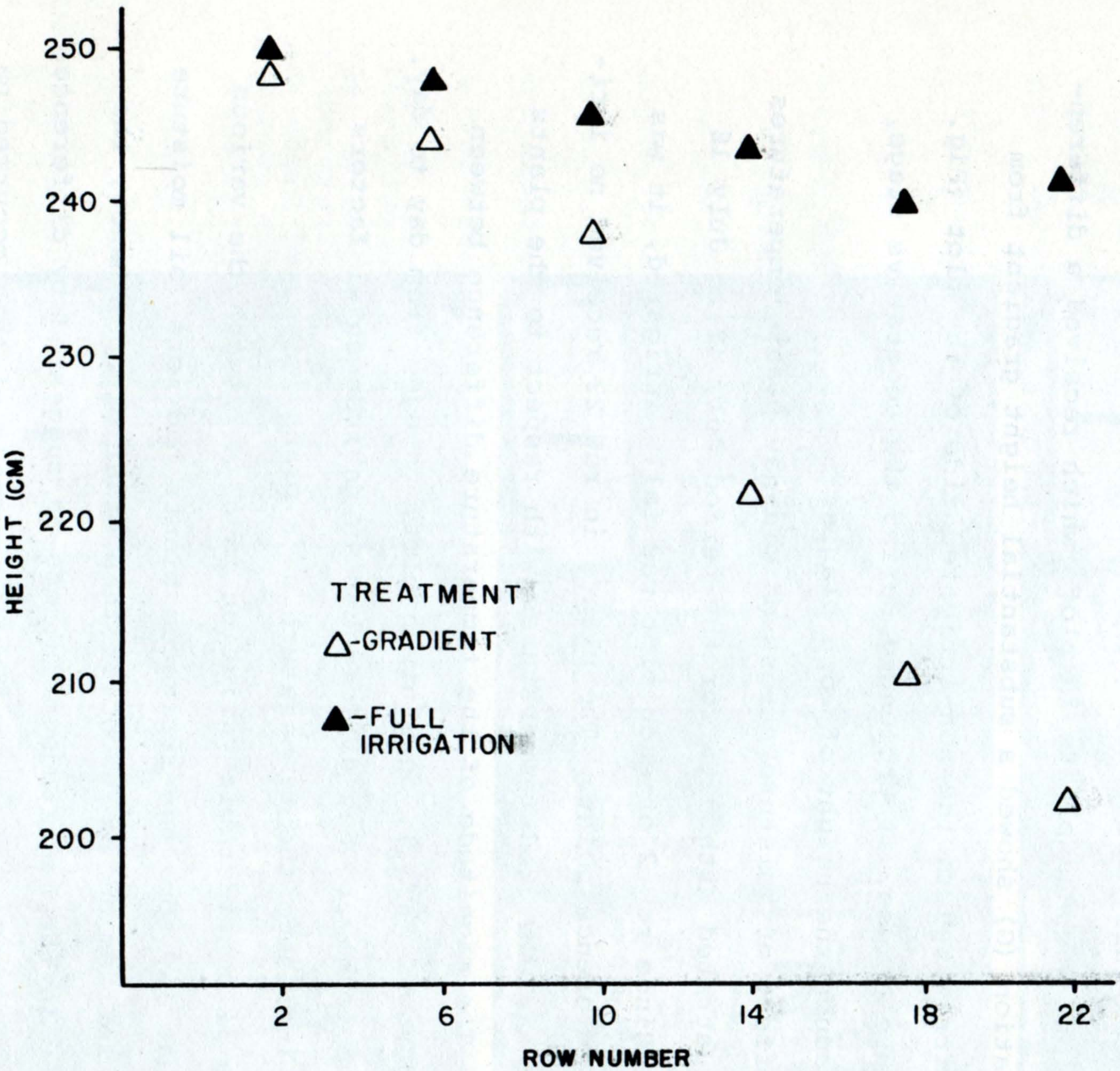

Fig. 7. Average height of corn plants by row. Measurements were made on July 21, 1978, near the end of the vegetative growth period.

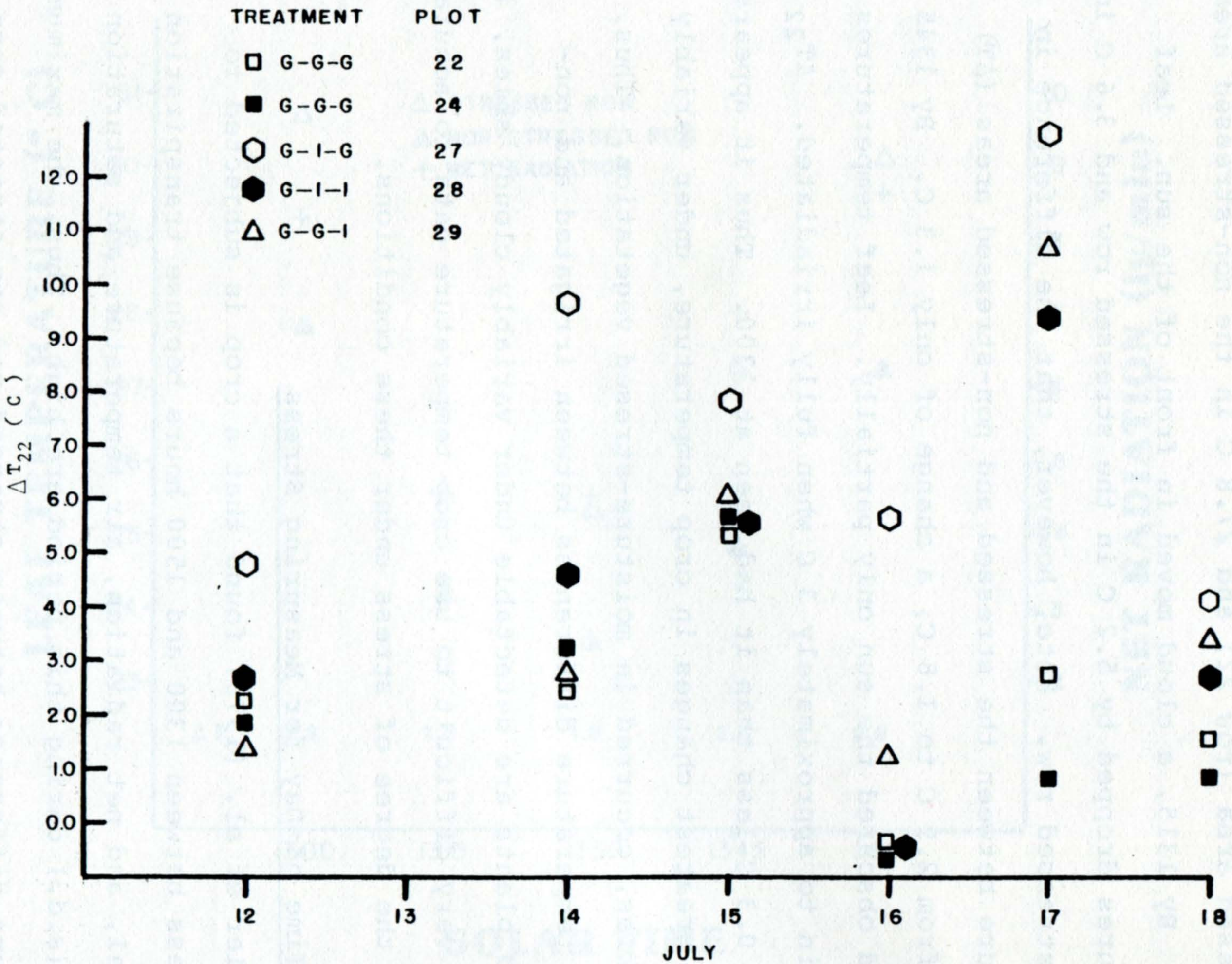

Fig. 8. Elevation in mid-day temperature of row 22 above that of row 2 (ΔT_{22}) for several corn plots. Each plot received a water gradient treatment during the vegetative growth stage. Data are for July 12-18, 1978.

Effect of Variable Cloud Cover on Crop Temperature Measurements

Partly cloudy skies create difficulties in observing crop temperature under field conditions. The effect of a transient cloud on leaf temperature is illustrated in Fig. 9. At 1300, plot 22 was fully irradiated. Leaf temperatures were 30.6 C in the stressed area (row 22) and 27.8 C in the non-stressed area (row 2). By 1315, a cloud moved in front of the sun. Leaf temperatures dropped by 5.2 C in the stressed row and 3.6 C in the non-stressed row. Note, however, that the difference in temperature between the stressed and non-stressed areas (ΔT) dropped from 2.9 C to 1.6 C, a change of only 1.3 C. By 1345 the cloud obscured the sun only partially. Leaf temperatures rose again to approximately 3 C when fully irriadiated. ΔT_{22} was only 0.3 C less than it had been at 1300. Thus it appears that the greatest changes in crop temperature, under variably cloudy skies, occurred in moisture-stresed vegetation. Thus, although temperature differences between irrigated and non-irrigated plants are detectable under variably cloudy skies, it would be very difficult to use crop temperature data to accurately quantify the degree of stress under these conditions.

Optimum Time of Day for Measuring Stress

Ehrler et al. (1978) found that a crop is subjected to high stress between 1300 and 1500 hours because transpiration is maximal, and net radiation, air temperature and saturation deficit (s.d.) during this period are high. Thus, the maximum temperature difference between stressed and non-stressed corn plants (ΔT_{max}) should occur during this period of the day. In

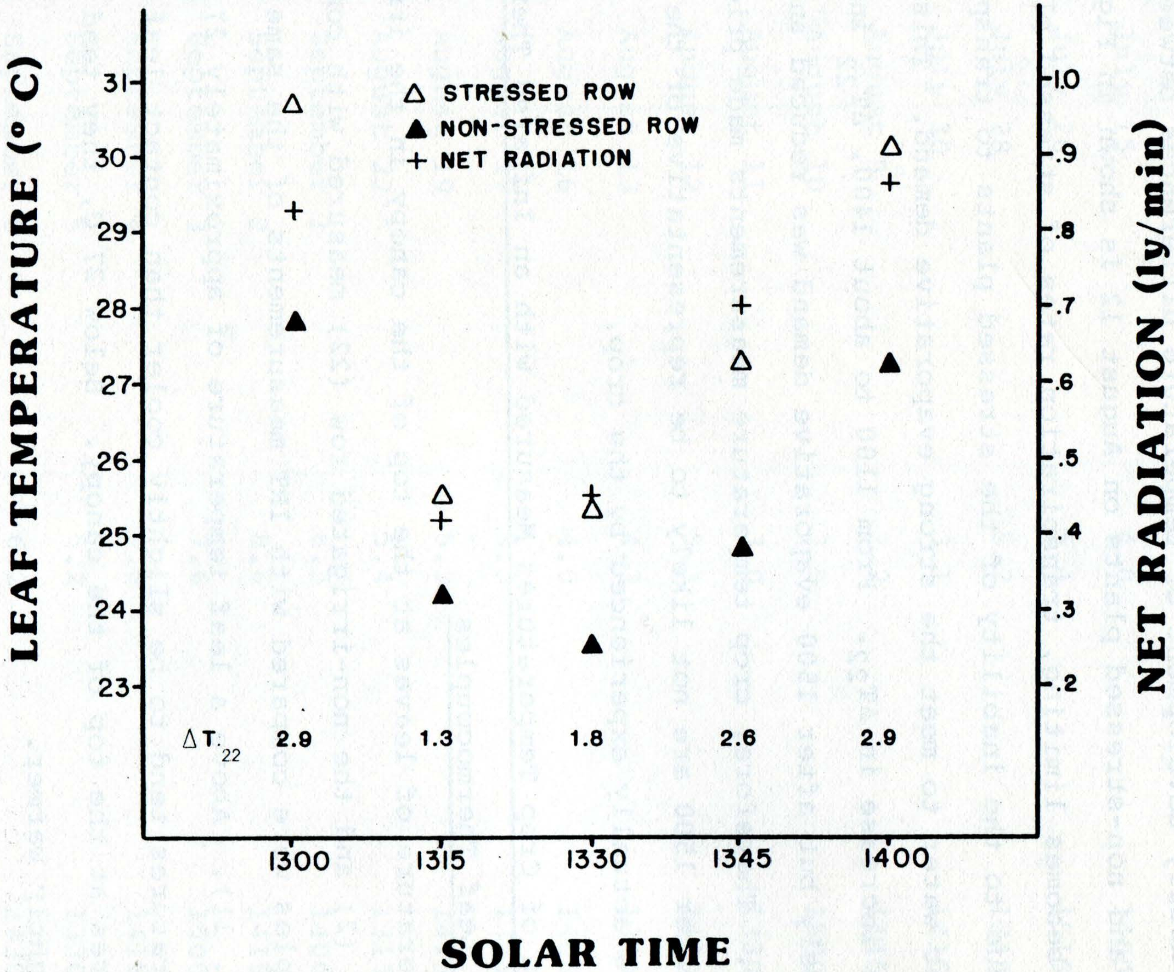

Fig. 9. Thermocouple temperatures of sunlit leaves (level 3) in row 2 (non-stressed) and row 22 (stressed) in plot 22 between 1300 and 1400 on July 7, 1978, a partly cloudy day. ΔT_{22} ($\Delta T_{22} = T_{22} - T_2$) is computed for each observation. Net radiation above row 2 is included to illustrate effects of clouds on the radiation flux density.

order to determine when ΔT_{max} occurs, we analyzed the diurnal leaf temperatures of sunlit leaves in rows 2 and 22 of plot 22 for 21 clear days between June 26 and September 6. In Table 1 it is seen that ΔT_{max} occurred between 1300 and 1500 throughout the season. For this reason we suggest measurement of ΔT_{max} at about 1400 hours.

The hourly development of temperature differences between stressed and non-stressed plants on August 12 is shown in Fig. 10. As water becomes limiting, transpiration rates of stressed plants decline due to the inability of the stressed plants to transpire sufficient water to meet the strong evaporative demand. This causes an increase in ΔT_{22}. From 1100 to about 1400, ΔT_{22} increased continuously but after 1500 evaporative demand was reduced and ΔT_{22} decreased. Therefore, crop temperature measurements made prior to 1300 or after 1500 are not likely to be representative of the maximum stress actually experienced by the crop.

Comparison of Crop Temperatures Measured with an Infrared Thermometer and Leaf Thermocouples

Temperature of leaves at the top of the canopy in the irrigated row (2) and the non-irrigated row (22) measured with contact thermocouples were compared with IRT measurements of the same rows (Fig. 11). Above a leaf temperature of approximately 27 C, IRT temperatures tend to be slightly cooler than contact leaf temperatures at the top of the canopy. Below 27 C, they tend to be slightly warmer.

IRT data represent an integration of the temperature of leaves at the top of the canopy, some leaves within the canopy

Table 1. Time of occurrence of maximal temperature differences (ΔT_{max}).

Date	ΔT_{max} (C)	Time of Day
June 26	5.0	1345
June 27	4.1	1315
July 15	4.0	1400
July 26	5.4	1515
July 28	5.2	1345
July 30	3.1	1415
August 5	2.2	1445
August 10	2.5	1500
August 11	3.0	1330
August 12	5.3	1430
August 13	4.3	1330
August 16	4.0	1400
August 17	5.3	1345
August 19	5.3	1415
August 22	5.4	1315
September 1	6.5	1400
September 2	8.4	1415
September 3	7.6	1500
September 4	9.9	1415
September 5	5.2	1330
September 6	6.2	1430

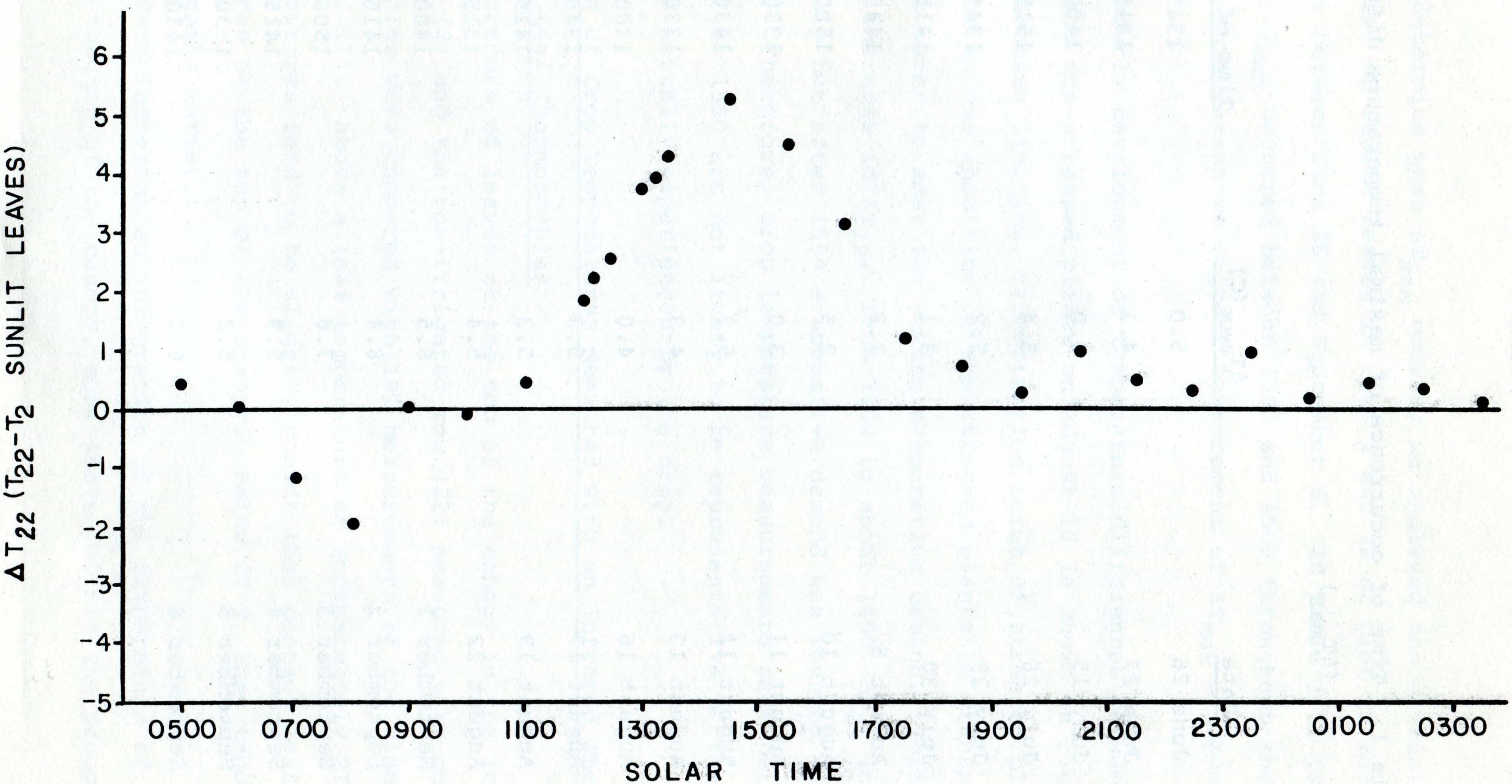

Fig. 10. Typical diurnal pattern of ΔT_{22}.

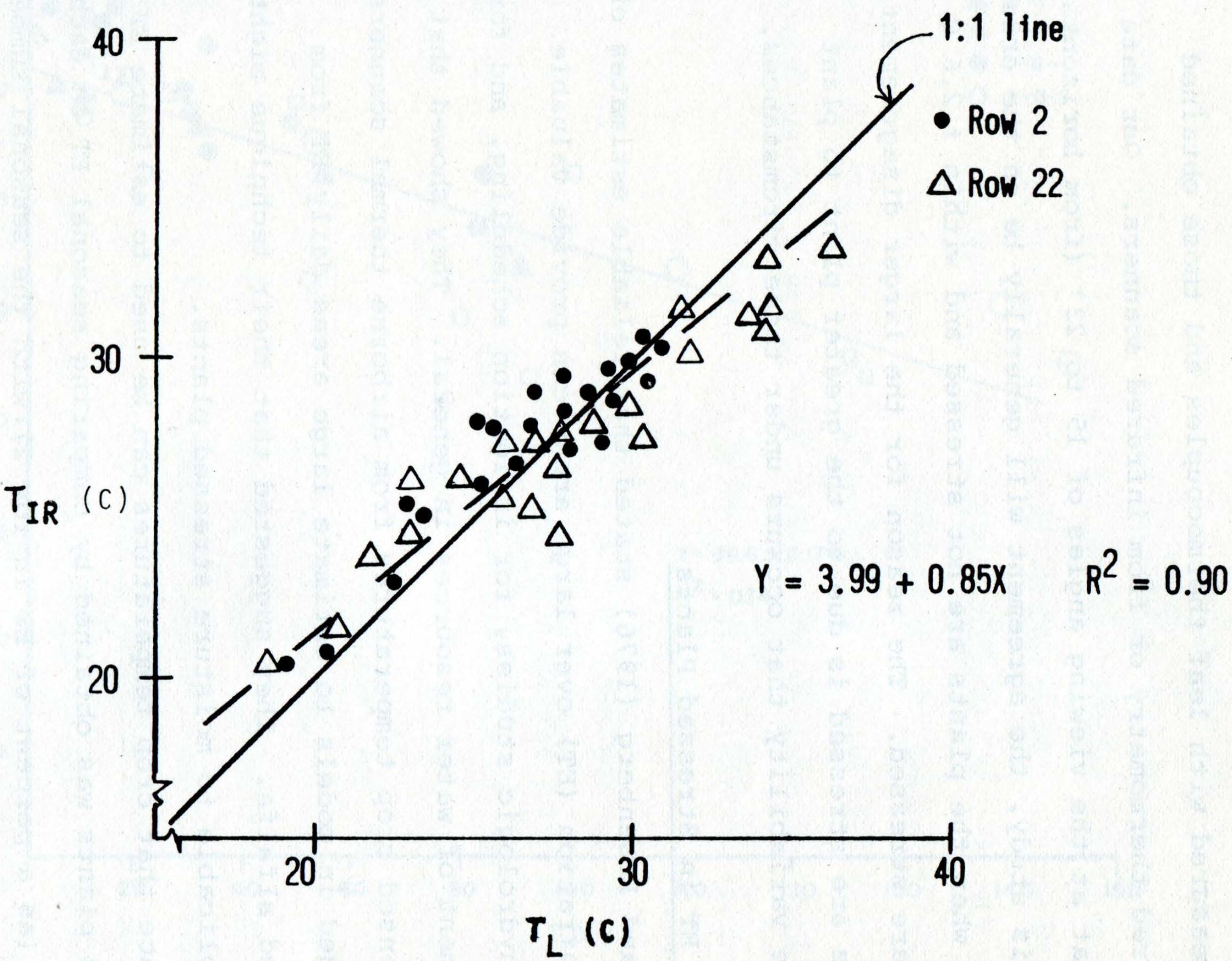

Fig. 11. Mid-day canopy temperatures (T_{IR}) and mid-day leaf temperatures (T_L) at the top of the canopy in row 2 (non-stressed) and row 22 (stressed) of plot 22 on 26 clear days between July 19 and September 6, 1978.

and any exposed soil that is viewed. The depth of view into the canopy of the IRT (or any other thermal scanner) depends on the viewing angle, the type of crop and the amount of crop cover. Thus, exact agreement should not be expected between crop temperatures measured with leaf thermocouples and those obtained from infrared thermometry or from infrared scanners. Our data suggest that at the viewing angles of 15 to 22° (from horizontal) used in this study, the agreement will generally be on the order of ± 1.2 C when the plants are not stressed and within ± 2.6 C when they are stressed. The reason for the larger disagreement when plants are stressed is due to the greater plant to plant temperature variability that occxurs under these circmstances.

Estimating ET in Stressed Plants

Blad and Rosenberg (1976) stated that reliable estimates of evapotranspiration (ET) over large areas can provide valuable input for hydrologic studies, for irrigation scheduling, and for the management of water resources in general. They showed that remotely sensed crop temperatures from airborne thermal scanners could be used in models to estimate large areas daily ET from non-stressed alfalfa. They suggested that their technique might also be applicable to moisture stressed plants.

Evidence that crop temperatures can be used to estimate ET in stressed plants was obtained by comparing seasonal ET on each sample row (as a percent of ET in row 2) with the seasonal summation of ΔT values (Fig. 12). Our data show that these reductions can be estimated to within ± 6% (standard error of estimate) with the use of crop temprature data.

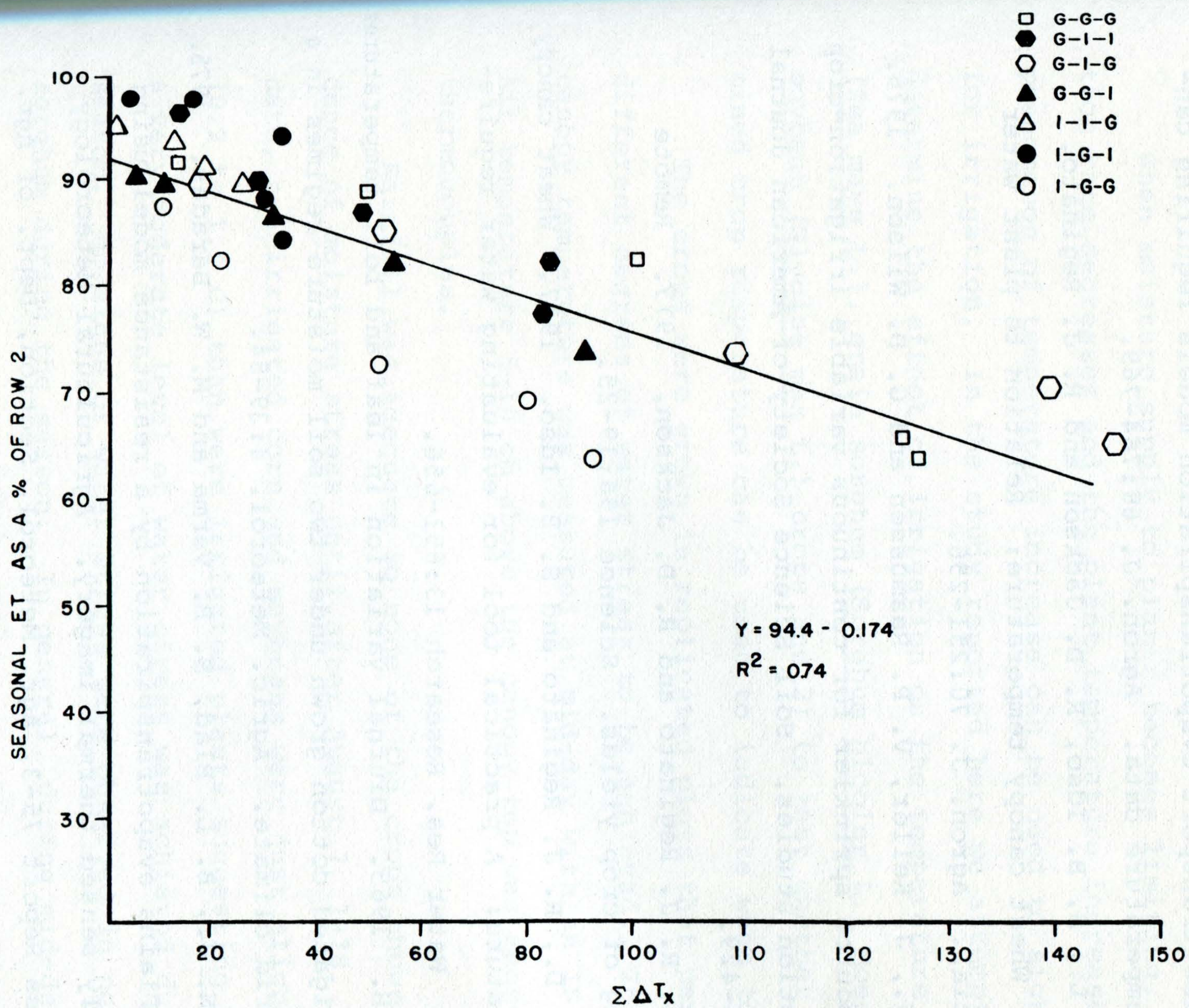

Fig. 12. Seasonal evapotranspiration (ET), expressed as a percent of ET in row 2, as a function of the sum of the difference in mid-day IRT temperature between row x (stressed) and row 2 (non-stressed) ($\Delta T_x = T_x - T_2$), x = 6, 10, 14, 18, 22.

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